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Load knowledge affects low-back loading and control of balance in lifting tasks

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This study investigated the effect of the presence or absence of load knowledge on the low-back loading and the control of balance in lifting tasks. Low-back loading was quantified by the net sagittal plane torque at the lumbo-sacral joint. The control of balance was studied by the position of the centre of gravity relative to the base of support, the horizontal and vertical momentum of the centre of gravity and the angular momentum of the whole body. In a first experiment, 8 male subjects lifted a rather heavy load (22% of body mass), using a leglift and a backlift, while they were familiar with the load mass. To counteract the threat to balance, imposed by picking up a load in front of the body, the subjects performed specific preparations, based upon the known load mass: prior to load pick-up, profound changes in the horizontal and angular momentum were found. The preparations were technique specific. Preserving balance seemed easier while picking up a load with a backlift than with a leglift. In the second experiment, 25 male subjects lifted a 6 kg box, which they expected to be 16 kg, because, in a series of lifts, the load mass was changed from 16 to 6 kg without their knowledge. Despite the 10 kg difference in actual load mass, the net torque at the lumbo-sacral joint was not different between lifting 6 and 16 kg, until 150 ms after box lift-off. Moreover, lifting of the overestimated load mass caused a disturbance of balance in 92% of the trials. The postural reactions aimed at regaining balance were not accompanied by an increased low-back loading. It was concluded that the absence of load knowledge, and the following overestimation of the load mass to be lifted, lead to an increased mechanical load on the lumbar spine and to an increased risk of losing balance in lifting tasks. Both events may contribute to a higher risk of low-back injury in manual materials handling tasks.

1. Introduction

In the industrialized world, the high prevalence of back injuries has developed into a well-recognized health problem. The associated costs in terms of loss of productivity, health care and individual suffering are unacceptably high. The life-time prevalance of low-back pain is estimated to be between 55% and 87% (Nicolaisen and Jørgensen 1985, Riihimäki 1985, Videman *et al.* 1984). Manual materials handling, especially lifting loads, is associated with low-back injuries (Andersson 1981, Chaffin and Park 1973, Klein *et al.* 1984). The high mechanical stress on the low back involved is assumed to be a major cause (Frymoyer and Pope 1978, Nachemson 1978). Falls, slips and trips that occur while lifting a load are also associated with low-back injuries (Manning and Shannon 1981). It is noteworthy that back injuries caused by falls are followed by longer sickness-absence and a higher rate of recurrence than accidental back injuries with other causes (Troup *et al.* 1981).

In many jobs, for example refuse collecting and luggage dispatching, the daily routine involves manual handling of loads with unknown mass. The 1-year prevalence of musculoskeletal complaints in the low-back region was 45% in refuse collectors (Stassen *et al*. 1993). Compared with other civil service workers, refuse collectors were more often declared unfit for work due to musculoskeletal injuries and neurological back problems (Verbeek and Geurts 1987). It might be hypothesized that the absence of load knowledge is a factor that contributes to the high prevalence of low-back injuries in refuse collectors. In lifting a load of unknown weight, the lifter may overestimate the weight and apply a larger force than is required to displace the actual load. As a result, the acceleration of lifter and load will be greater than expected and the lifter will move upward rapidly in an uncontrolled manner (Butler *et al*. 1993, Patterson *et al*. 1987). In this case, three adverse effects of the lack of load knowledge can be put forward. In the first place, the lifter can fall and strike the (low) back against an object or the floor. One per cent of the lumbo-sacral injuries reported in a gearbox factory was attributed to this event (Manning and Shannon 1981). In the second place, the overestimate of the load mass will cause greater forces at the hands and, consequently, at the low back than actually needed for that particular lift. Experimental studies that investigated the effect of load knowledge on low-back loading, found that lifting an object with versus without load knowledge resulted in an increased lumbo-sacral loading in the latter condition (Butler *et al*. 1993, Patterson *et al*. 1987). Third, the postural reactions required to regain balance could be hazardous to the low-back musculoskeletal system, as suggested by Oddsson (1990). Epidemiological studies have indeed shown that workers exerting sudden unexpected maximal efforts are particularly vulnerable to low-back disorders (Magora 1973).

Efforts to reduce the incidence of low-back pain at the workplace are often based upon the evaluation of manual materials handling tasks, in which several load determining factors are involved, e.g. the load location, the displacement of the load, the asymmetry of lifting, the lifting frequency, the coupling between load and hands. The NIOSH equation provides a method for computing a weight limit for manual lifting from these factors (Waters *et al*. 1993). The (absence of) load knowledge, however, is a factor that is not accounted for in this equation, nor in any other evaluation approach.

Load knowledge proved to be essential in lifting small objects with a precision grip, because the vertical lifting force pattern was found to be scaled to the object's weight (Forssberg *et al*. 1992). In bimanual lifting tasks involving the whole body, a similar scaling of the vertical force pattern can be assumed, for which adequate load knowledge would be required. Moreover, correct knowledge about the load mass to be lifted seemed important to make adequate preparations to counteract the threat to balance that is imposed upon the lifter by picking up a load in front of the body (Commissaris and Toussaint 1995).

The present study was aimed at gaining more insight into the effect of (the absence of) load knowledge on low-back loading and the control of balance in bimanual, whole-body lifting tasks. The mechanical load on the lumbar spine and the control of balance were studied in lifting tasks, in which subjects did have load knowledge and in tasks in which subjects did not always have the correct load knowledge. The authors first investigated how the lifter prepared himself to counteract the threat to balance that is imposed by picking up a rather heavy load in front of the body. Next, the authors investigated whether the low-back loading was indeed increased in case subjects overestimated the load mass to be lifted and in case subjects showed postural reactions to prevent falling. Furthermore, the reasons for losing balance when subjects overestimated the load mass were studied.

2. Methods

2.1. *Experiment I*

2.1.1. *Subjects and procedures:* Eight healthy male subjects (means $\pm$ 1 standard deviation: age, 22·3 $\pm$ 1·5 years; body height, 1·79 $\pm$ 0·07 m; body mass, 71 $\pm$ 11·7 kg; footlength, 0·267 $\pm$ 0·067 m) participated in the experiment after they had given written informed consent and after approval of the Institute's ethical committee. None of the subjects reported a history of low-back disorders or other motor impairments.

In an ongoing downward and upward movement, the subjects were asked to pick up and lift a barbell and to come to a full stop holding the barbell at acromion height, using a leglift (straight back, bent legs) and a backlift (straight legs, bent back) (figure 1). Several measures were taken to enhance the threat to balance that is imposed upon the lifter by picking up a load in front of the body and thus, to enhance the necessity to make adequate preparations beforehand. (1) The barbell was fairly heavy, 22% of the subject's body mass. (2) The barbell was placed in front of the toes, at such a distance that the subject was just able to pick it up (heel-barbell distance 0·615 $\pm$ 0·054 m). This distance was similar for both lifting techniques. (3) In a series of 10 to 15 trials (for each technique condition), the lifting speed was increased for each succeeding trial, until the subject was no longer able to preserve balance (the duration of one downward movement phase thus decreased from *c*. 1·2 to *c*. 0·5 s). Imbalance was judged to occur when the heels lost contact with the ground or when a compensatory step was made to prevent falling.

Lifting speed was imposed by means of an acoustic metronome. Subjects first performed several movement cycles without picking up the load. When the required rhythm was attained, one of the authors counted down to the moment of barbell lift-off, starting at the beginning of the penultimate downward phase. To standardize the execution of the lifting tasks, the subjects were instructed to restrict their movements to the sagittal plane, to keep the heels on the ground at load pick-up and to guard their balance throughout the movement. In the lowest position, the vertical distance between the load and the ground was standardized at 14% body height. Subjects were instructed to lift the barbell in a straight vertical line, indicated by two flexible metal wands that were positioned in front of the barbell at the left and right end (from the subject's perspective). They performed practice trials to familiarize themselves with the tasks.

2.1.2. *Linked segment model, kinematics and kinetics:* The last two lowering-lifting cycles (figure 1) were recorded using a 3-D semi-automatic video-based motion registration system (VICON^{TM}, Oxford Metrics Ltd). Reflective markers (ϕ = 25·4 mm) were attached to the skin (right side) to indicate the location of the fifth metatarsophalangeal joint, the ankle joint (distal part of the lateral malleolus), the knee joint (lateral epicondyle), the hip joint (greater trochanter), the lumbo-sacral (L5-S1) joint (as in de Looze *et al.* 1992a), the spinous process of the first thoracic vertebra, the head (caput mandibula), the lateral border of the acromion, the elbow joint (lateral epicondyle), the wrist joint (ulnar styloid), and the hand (a small stick attached to the third metacarpus). An additional marker was attached to the right end of the barbell (from the subject's perspective). The coordinates of the acromion marker were used to determine the position of the shoulder joint. The length of the base of support was inferred from markers placed on the heel and the distal end of the most prominent toe. The coordinates of the joint positions defined 8 body segments in the sagittal plane: the feet, lower legs, upper legs, pelvis, trunk/head, upper arms, forearms and hands(/load). The marker positions were sampled at 60 Hz and the raw sagittal plane coordinates were low-pass filtered with a digital filter (zero phase lag, 2nd order Butterworth, 5 Hz). Anthropometric data (body mass, length of segments) were measured. The mass of each segment, the positions of the segmental centres of gravity (CoG), except for the trunk, and the moments of inertia were calculated according to Plagenhoef *et al.* (1983) and de Looze *et al.* (1992a). The mass, inertia and location of the CoG of the hands were adapted at the instant the hands grasped the load. The coordinates of the markers on the spinous process of the first thoracic vertebra and L5-S1 joint were used to determine the position of the trunk CoG during the movement according to an optimization procedure, which improved the estimated trajectory of the total body CoG (Kingma *et al.* 1995). The angles of each segment were calculated relative to the right horizontal. Numerical differentiation (Lanczos 5-point differentiation filter) of the time histories of the segment angles and CoG positions yielded (angular) velocities and accelerations.

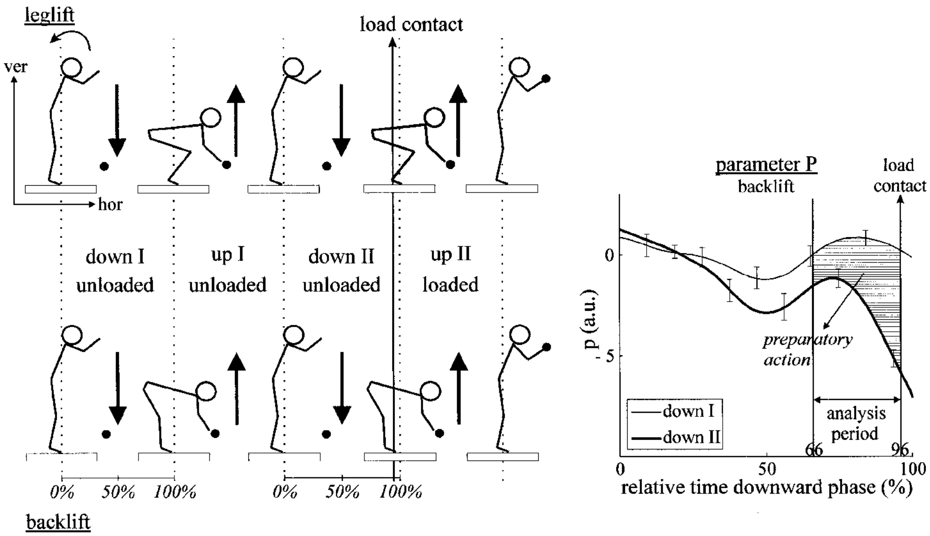

Figure 1. Two sequences of stick-figures illustrate the protocol of experiment I (left panel). Subjects lifted a barbell (up II) after several unloaded movement cycles, using a leglift (upper row) or a backlift (lower row). Two complete movement cycles were recorded (down I, up I, down II and up II). The beginning of a downward phase (at the highest body centre of gravity position) was defined 0% relative time and the end (at the lowest body centre of gravity position) was defined 100%. The moment of load contact occurred at 96% relative time. Positive directions for translation and rotation are shown in the upper left stick-figure. The right panel illustrates an example of a preparatory action (i.e. a significant difference between down II and I in the last 30% before load contact, hatched area) in a (fictitious) parameter P for the backlift.

The ground reaction force was recorded by means of a strain gauge force platform ($1{\cdot}0 \times 1{\cdot}0$ m). The analogue force signals were amplified, low-pass filtered (30 Hz, 4th order), sampled (60 Hz, 12 bits) and stored synchronously to the movement registration by the VICON-system. For translations, the caudo-cranial and dorso-ventral directions were defined positive and for rotations the counter-clockwise direction (figure 1, upper left stick-figure).

2.1.3. *Biomechanical analysis:* To obtain an estimate of the mechanical load on the lumbar spine, the net sagittal plane torque at the lumbo-sacral joint ($T_{L5\text{-}S1}$) was determined by means of inverse dynamic analysis (Elftman 1939) using the dynamic 2-D linked segment model described by de Looze *et al.* (1992a). To study the control of balance, the position of the CoG relative to the base of support (CoG_{rel}), the horizontal and vertical momentum of the centre of gravity (p_{hor}, p_{ver}) and the angular momentum of the whole body (L) were determined. In a static situation, such as upright standing, the CoG_{rel} has to remain within the borders of the base of support (Massion 1992). In a dynamic situation, such as load lifting, other criteria for maintaining balance are operative such as confining the linear and angular momenta to certain limits during task execution (Toussaint *et al.* 1995). The parameters were determined as follows, according to Toussaint *et al.* (1995):

- CoG_{rel}: the horizontal position of the CoG of the body (including the load after pick-up), expressed as a percentage of the base of support (heels at 0% and toes at 100% CoG_{rel}).
- p_{hor} and p_{ver}: the instantaneous horizontal and vertical momentum of the CoG of the body (including the load after pick-up), calculated from, respectively, the sum of the horizontal and the sum of the vertical momenta of all segmental CoGs.
- L: the instantaneous angular momentum of the body (including the load after pick-up) around a rotation axis situated in the body's CoG, calculated from the sum of the segmental angular momenta.

2.1.4. *Data analysis and statistics:* The duration of all individual curves of a downward phase was normalized to 100% (figure 1, left panel). The moment of barbell contact was defined four samples (67 ms) before the vertical displacement of the barbell exceeded 2·5 mm. The 194 successfully recorded trials were marked by one of the authors as 'balance' (115) or 'imbalance' (79), according to the criteria mentioned above. The latter category was not further analysed. To identify any specific preparations, kinematics and kinetics of the last downward phase (down II, figure 1), before the barbell was lifted, were compared with the same parameters of the previous downward phase (down I, figure 1), after which no load was lifted. A difference between both phases would be indicative of preparatory actions, of which an example is shown in the right panel of figure 1. Before load contact, the values of parameter P in downward phase II decrease relative to the values of downward phase I. A significant difference between down II and I in the analysis period (see below) is considered to be a preparatory action.

A repeated measures multivariate analysis of covariance (MANCOVA) was performed on the five biomechanical parameters (dependent variables), with downward phase (down I, down II) and lifting technique (leglift, backlift) as within-subject factors, with subject (1 to 8) as between-subject factor and the average speed of the body CoG in both downward phases as a covariate. From the 115 balance trials, 40 leglift and 40 backlift trials were selected, such that each leglift-backlift pair was from the same subject, yielding 40 cases with 2^2 independent variable levels per case. For each parameter and each independent variable level, the last 30% of the downward phase *before* barbell contact (analysis period, figure 1) was averaged and tested in the MANCOVA. This period was arbitrarily chosen, because testing at one point in time might fail to reveal a main effect, whereas analysing a period longer than 30% might average existing parameter changes too much. For each parameter, univariate F-tests were applied to interpret the overall effects. Effects were considered to be significant at $p < 0{\cdot}05$.

2.2. *Experiment II*

2.2.1. *Subjects and procedures:* Twenty-five healthy male subjects (age, $22{\cdot}8 \pm 2{\cdot}0$ years; body height, $1{\cdot}78 \pm 0{\cdot}03$ m; body mass, $73{\cdot}4 \pm 9{\cdot}9$ kg) participated in this experiment. None of them reported a history of low-back disorders or other motor impairments. All subjects were informed that they had to perform a series of tasks, in which a box of which the mass ranged from 6 to 16 kg was to be lifted. They were not informed about the sudden changes in load mass that were going to take place. The Institute's ethical committee approved of the experimental set-up and the risk of falling backward involved with overestimating the load mass to be lifted. In a pilot study the authors established that an actual fall never occurred because of adequate postural reactions. After the experiment, the subjects were kindly requested not to reveal the experimental set-up to others.

Subjects were induced to overestimate the weight to be lifted, because they first lifted a box of 16 kg for two, three or four times (randomly assigned) and then lifted a box of 6 kg, only once. To make sure that subjects would expect to lift the 16 kg box instead of a 6 kg box, two black PVC boxes of equal size ($0{\cdot}24 \times 0{\cdot}34 \times 0{\cdot}42$ m) and colour, but different mass (6 kg versus 16 kg) were used. Upon completion of each lift, the subject was instructed to turn around. One of the authors removed the box and replaced the same or another box after 30 s. In this way, the expectation pattern of lifting 16 kg boxes was suddently disrupted, leading to an overestimation of the weight of the 6 kg box. Imbalance in a trial was judged to occur when the forefoot lost contact with the ground or when a compensatory step was made to prevent falling. Subjects were instructed to lift as quickly as possible to prevent them from perceiving the actual load mass in the initial part of the lift. The duration of the upward movement phase was about 1 s.

The subjects were standing in front of a box and upon a sign from one of the authors flexed forward, grasped the box and lifted it to return to an upright position with the box held aloft at breast height. The CoG of the box, indicated by three reflective markers on the right side of each box, was placed 0·30 m in front of the subject's toes. The subjects were instructed to keep the heels on the ground at load pick-up, to restrict their movements to the sagittal plane and to guard their balance throughout the movement. No specific instructions were given regarding lifting technique. The subjects performed practice trials using the 16 kg box to familiarize themselves with the experimental task. Each subject performed at least two series of lifts, separated by a 15-min pause. Although most subjects expected the sudden change in weight on the second series, the strict instructions, high lifting speed and unexpectedness of the change constrained them to perform the second series just as the first one.

2.2.2. *Linked segment model, kinematics and kinetics:* The kinematics, kinetics and linked segment model of experiment II were similar to those of experiment I. For each trial, data collection started *c*. 0·5 s prior to the start of the lift and ended at the moment the subject was standing completely erect again.

2.2.3. *Biomechanical analysis:* The biomechanical analysis of experiment II was identical to that of experiment I.

2.2.4. *Data analysis and statistics:* To permit averaging of trials, each trial was synchronized in time to the moment ($t = 0$) the displacement of the CoG of the box exceeded 5 mm (box lift-off). A total of 81 samples were taken into analysis, 20 before box lift-off and 60 thereafter. An imbalance trial, resulting from lifting the overestimated load mass, was matched with the balance trial preceding it, yielding two experimental conditions: '16 kg' (balance) and '6 kg' (imbalance).

To examine the effect of weight overestimation on the low-back loading and the control of balance, the biomechanical parameters of lifting the 16 kg box were compared with those of lifting the 6 kg box, which was expected to be 16 kg. A multivariate analysis of variance (MANOVA) was performed on the complete time traces of the five biomechanical parameters, with 50 cases and with experimental condition (16 kg, 6 kg) and time (81 samples) as between-subject factors. Univariate F-tests were applied to interpret the overall effects and effects were considered to be significant in case of $p < 0{\cdot}05$.

3. Results

3.1. *Experiment I*

Figure 2 shows the five parameters studied in relation to the preparatory actions that a lifter performs before picking up and lifting a load. In each panel four time traces are displayed, representing different combinations of downward phase (I, II) and lifting technique (leglift, backlift).

The pick-up of the load induces a quick forward shift of the projection of the CoG on the ground (CoG_{rel}). The upper right panel depicts a part of this forward shift: from load contact onwards (96%) the time traces of down II increased quickly for both lifting techniques, i.e. the CoG_{rel} moved towards the toes. This is a balance-threatening event, because the CoG approached the front margin of the base of support. Furthermore, picking up the load in front of the body brakes the counter-clockwise (positive) angular momentum L of the body towards an erect standing posture (not visible in figure 2). Since L was only small at that time (about zero at the end of downward phase I, upper left panel), load pick-up induced a risk of toppling forward.

To counteract these threats to balance, preparatory actions were performed. For the leglift, the CoG_{rel} was positioned more towards the heels at the end of down II compared with I and p_{hor} (middle left panel) decreased considerably. For both techniques L was larger at the end of downward phase II, attaining positive values before load contact. Parameter p_{ver}, however, did not display a preparatory action (middle right panel) and $T_{L5\text{-}S1}$ (lower panel) was larger at the end of downward phase II for the leglift only. As can be deduced from the presence or absence of hatched areas in figure 2, the preparatory actions were not always similar for the two lifting techniques. For instance, in leglifting the CoG_{rel} was positioned more towards the heels in down II, compared with I, whereas in backlifting it was positioned a little more towards the toes in down II.

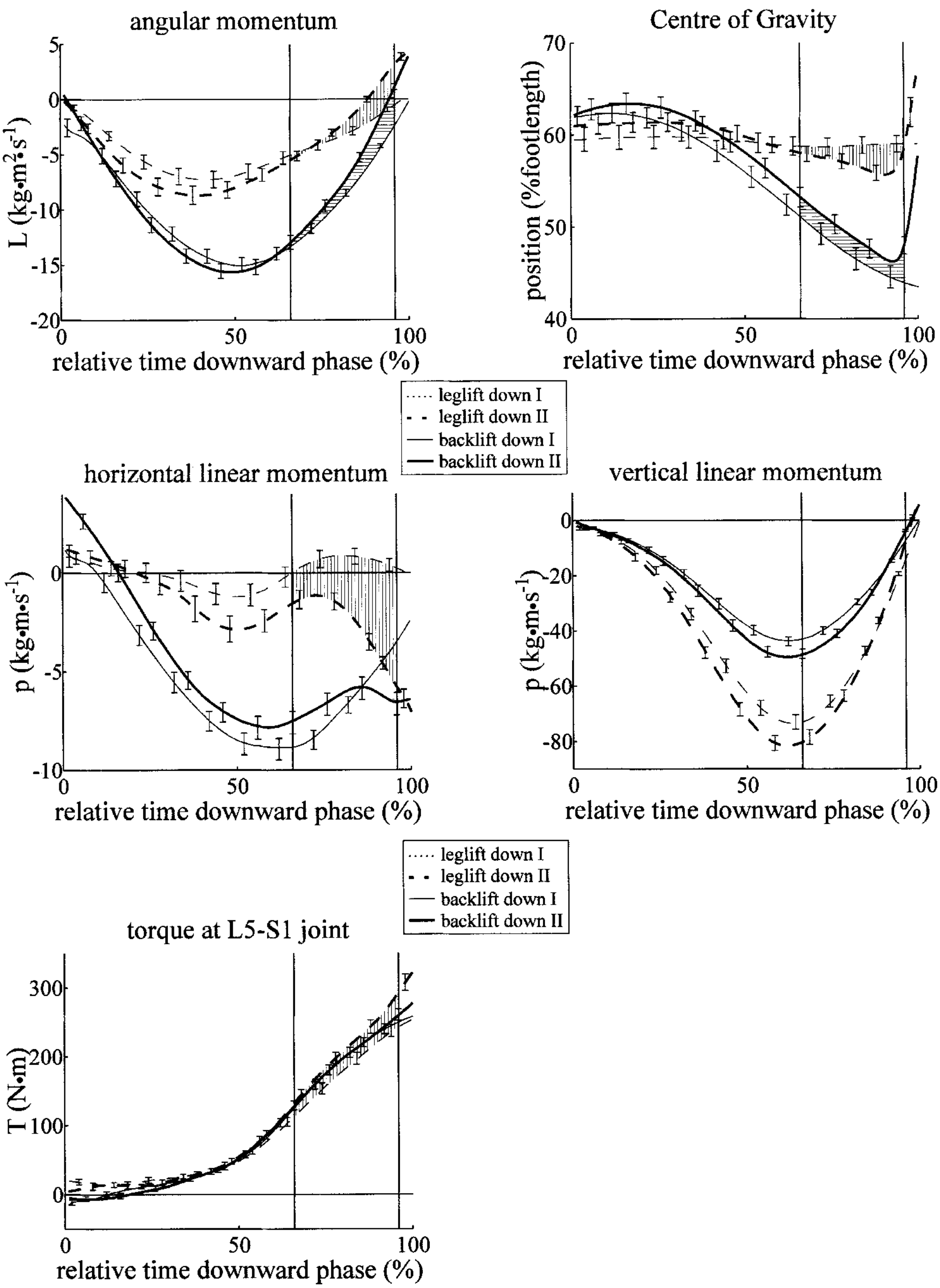

Figure 2. Time traces of two downward phases (I and II) of a lifting task for the angular momentum (upper left), the horizontal position of the centre of gravity relative to the base of support (upper right), the horizontal and vertical linear momentum (middle panels) and the lumbo-sacral (L5-S1) torque (lower panel) for the leglift and backlift. Mean time trace ($n = 40$) $\pm$ 1 standard error of the mean are shown. Conventions as in figure 1, with the vertically hatched area marking a preparatory action during leglifting and the horizontally hatched area during backlifting.

The differences between both downward phases were found to be significant (MANCOVA, Wilk's lambda = 0·131, $F = 37{\cdot}249$, $p < 0{\cdot}05$), indicating that subjects prepared themselves before picking up the load. The preparatory actions were not the same for both lifting techniques, because a significant interaction effect between downward phase and technique was found (Wilk's lambda = 0·301, $F = 13{\cdot}014$, $p < 0{\cdot}05$). Table 1 summarizes the univariate test results, presenting the differences between both downward phases for each lifting technique.

3.2. *Experiment II*

3.2.1. *Movement characteristics of the lifting task:* The attempt to wilfully induce a loss of balance by creating an overestimation of the object's weight was successful in the second experiment: in 92% of the lifting trials, in which the box's weight was 6 kg instead of 16 kg, subjects showed signs of compensatory responses such as lifting of the forefoot or making a backward step to prevent falling. Two sequences of stick-figures in figure 3 represent the average movement performed during the last part of the unloaded downward phase and the complete loaded upward phase for both experimental conditions. The subject picked up the box in a continuous motion and lifted it in a vertical line to breast height. The stick-figures of the 16 kg trials closely resemble those of the 6 kg trials, especially before the box is grasped. However, some differences are noticeable after box lift-off: from 250 to 717 ms the subjects extended their backs faster in the 6 kg trials than in the 16 kg trials. Some compensatory movements are visible from 250 ms onwards: subjects held the box further in front of the body and made a backward step, indicated by the backward shifted foot-segment.

3.2.2. *The effect of overestimating the load mass on low-back loading and control of balance:* When unexpectedly presented with the 6 kg box, subjects did not prepare themselves to lift the 6 kg box, but the expected 16 kg box. Thus, biomechanical parameters should be the same prior to lifting the 16 kg versus the 6 kg box. Furthermore, the biomechanical parameters should picture the signs of imbalance when lifting the overestimated load mass. Figure 4 shows the time traces of the five biomechanical parameters for both experimental conditions, from 333 ms before box lift-off until 1000 ms thereafter.

Table 1. Differences between downward phase I and II for five biomechanical parameters, presented for the two lifting techniques separately. The signs '↑' and '↓' represent, respectively, a significant increase and decrease in the mean parameter value during the analysis period from downward phase I to II, while '0' indicates that no significant difference was found. *denotes a significant difference in preparation between techniques.

Parameter		Lifting technique Leglift ($n = 40$)	Backlift ($n = 40$)	Significant difference
p_{hor}	(kg m s^{-1})	↓	0	*
p_{ver}	(kg m s^{-1})	0	0	
CoG_{rel}	(% foot length)	↓	↑	*
L	(kg m^2 s^{-1})	↑	↑	
$T_{L5\text{-}S1}$	(N m)	↑	0	*

Figure 4 clearly shows no difference between the time traces of both experimental conditions prior to grasping the box. This finding was confirmed by the results of the MANOVA, performed on the times traces of the five biomechanical parameters. A significant interaction effect of experimental condition and time was found (Wilk's lambda = 0·548, $F = 12{\cdot}665$, $p < 0{\cdot}05$), indicating that the time traces of lifting the 16 kg box were indeed different from those of lifting the 6 kg box, but not during the whole time period analysed. Periods of significant differences between the two conditions are hatched in the graphs. The univariate analyses revealed a significant difference between both conditions around box lift-off for parameters L and CoG_{rel} (upper panels), at + 17 ms and —33 ms, respectively. For p_{hor} and p_{ver} (middle panels) the deviation started longer after box lift-off, at 100 ms in both cases. The finding that $T_{L5\text{-}S1}$ (lower left panel) was different between both conditions first after 150 ms implies that the peak low-back loading was similar when lifting a 16 kg box and when lifting a 6 kg box. Thus, the absence of load knowledge, and the subjects' assumptions that the box was 16 kg instead of 6 kg, resulted in a low-back loading that would accompany the lifting of a 16 kg box. Only after box lift-off the subjects sensed that the box was lighter than 16 kg and gradually the low-back loading became less than the low-back loading of lifting a 16 kg box. However, this does not confirm the hypothesis that the overestimation of the load mass to be lifted resulted in an increased mechanical load on the lumbar spine. Therefore, the authors repeated this experiment and extended the protocol: after lifting of the overestimated

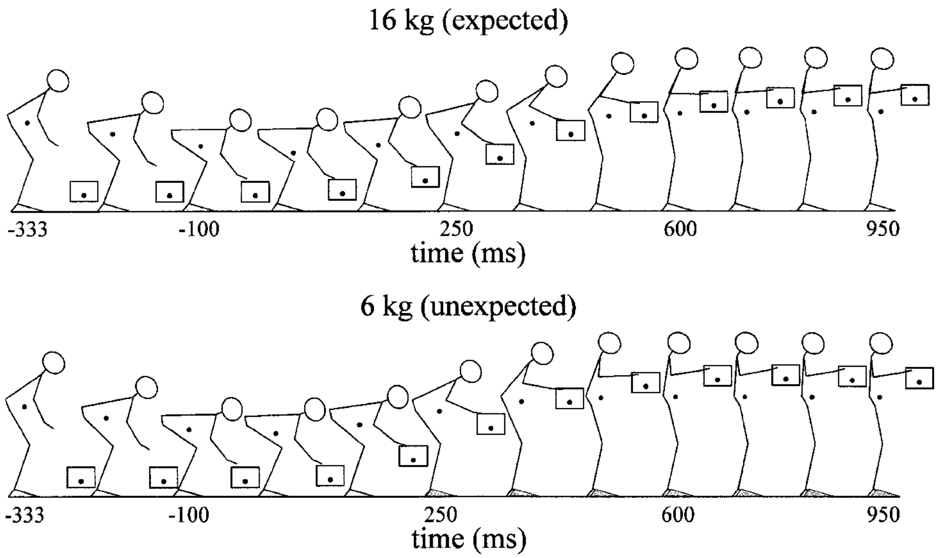

Figure 3. Two sequences of stick-figures represent the average movement of subjects during 50 'expected 16 kg' trials (upper row) and 50 matched 'unexpected 6 kg' trials (lower row). The centre of gravity of the whole body and of the box are indicated by dots. The first stick-figure is at 20 samples (333 ms) before time 0, which was the moment at which the vertical displacement of the box's centre of gravity exceeded 5 mm. The time interval between two adjacent stick-figures is 7 samples (117 ms). In the last 7 stick-figures of the lower row, the (additional) shaded foot segment displays the foot position at $t = 250$ ms to indicate that some subjects made a backward step.

load mass, the subjects lifted that box for another three times while they knew that the load mass was reduced. Eight (other) healthy male subjects lifted a box, which was provided with force transducers in the handles, using a freely chosen lifting technique and speed. They first lifted a 16·7 kg box four times, then lifted a 6·7 kg box which they expected to be 16·7 kg and finally lifted this 6·7 kg box three times knowing its actual weight. One series of eight trials was performed per subject. In the fifth trial, all subjects indeed overestimated the load mass to be lifted and they had to make compensatory responses after box lift-off. The lower right panel of figure 4 again shows that $T_{L5\text{-}S1}$ was not different in the initial part of the upward phase when lifting the 'expected' 16·7 kg box and the 'unexpected' 6·7 kg box; peak $T_{L5\text{-}S1}$ was not significantly different (309·75 versus 303·29 N m, $t = 0.92$, $p = 0.387$). However, lifting of the 'unexpected' 6·7 kg box did significantly increase $T_{L5\text{-}S1}$ during the first period after lift-off when compared with lifting of the 'expected' 6·7 kg box (peak $T_{L5\text{-}S1}$ 303·29 versus 248·82 N m, $t = -5.90$, $p < 0.05$). From *c*. 175 ms after lift-off onwards, the $T_{L5\text{-}S1}$ curves in both 6·7 kg conditions were similar, suggesting that the subjects had adjusted their movement pattern and force generation on the box to the actual weight.

Figure 4 also shows what happened with respect to the control of balance. Overestimating the load mass caused an 'overshoot' in the linear momenta. Just after box lift-off, the negative (backward) p_{hor} reached a larger value in the 6 kg trials than in the 16 kg trials. Likewise, the positive (upward) p_{ver} increased more when the 6 kg box was lifted. The positive (counter-clockwise) L showed an overshoot too when the overestimated load mass was lifted. Thus, the linear and angular momenta were larger than expected, leading to imbalance and compensatory reactions to regain balance. These reactions were not accompanied by a higher low-back loading; the 6 kg $T_{L5\text{-}S1}$ did not show an overshoot.

4. Discussion

4.1. *Keeping balance when picking up a load of known mass*

Picking up a load in front of the body induced a risk of toppling forward, because the body's CoG quickly shifted forward and the counter-clockwise angular momentum of the body towards an erect posture was braked. Hence, the projection of the CoG on the ground approached the front margin of the base of support and a smooth extending movement of the subject was hampered. Apparently, the subjects successfully minimized the adverse effects of these balance-threatening events, since balance was not lost. This was accomplished by specific preparations prior to load pick-up, demonstrated in experiment I. A discussion of the preparations from a motor control point of view can be found in Commissaris and Toussaint (in press) and Toussaint *et al.* (submitted b).

In the first place, the adverse effect of the forward CoG shift was reduced by the preparatory change in the CoG momentum p_{hor}. During leglifting, a profound backward p_{hor} was created prior to load pick-up, to brake the forward CoG shift and thus prevent that the CoG_{rel} approached or even crossed the front margin of the base of support after load pick-up. During backlifting, a decrease in the backward directed p_{hor} occurred close to load pick-up, but it was not significant. Without preparation (see down I in figure 2), the backward p_{hor} would have been smaller or p_{hor} would even have been directed forward. In the second place, the adverse effect of a braked counter-clockwise angular body momentum L was reduced by a preparatory increase in L for both techniques. Without the preparatory increase in

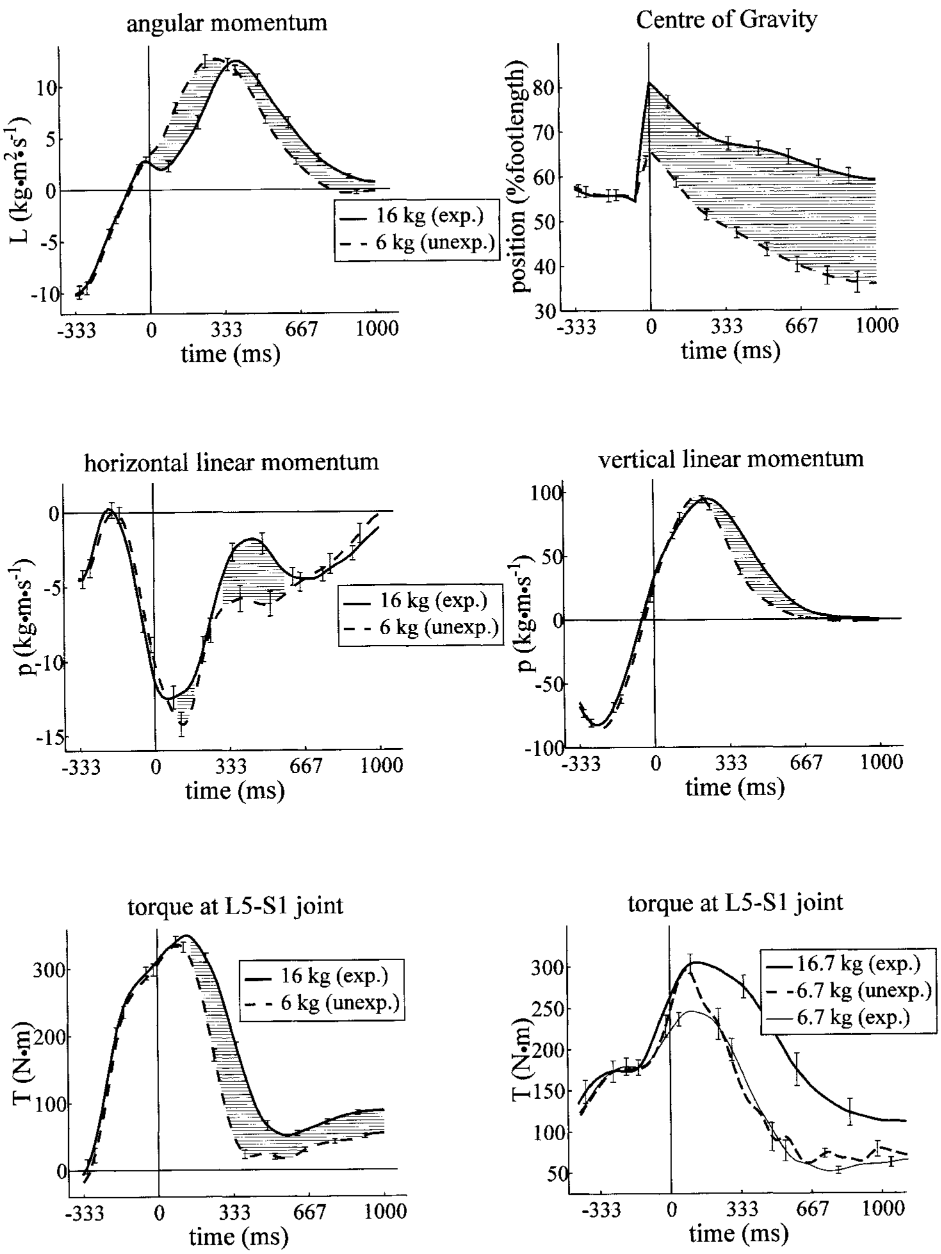

Figure 4. Time traces of two different lifting tasks (lifting 16 kg versus lifting 6 kg that was expected to be 16 kg) for the angular momentum (upper left), the horizontal position of the centre of gravity relative to the base of support (upper right), the horizontal and vertical linear momentum (middle panels) and the lumbo-sacral (L5-S1) torque (lower left panel). Mean time trace ($n = 50$) $\pm$ 1 standard error of the mean are shown. Time 0 indicates box lift-off, the moment at which the vertical displacement of the box's centre of gravity exceeded 5 mm. Periods of significant differences between the two experimental conditions are hatched.

L (see down I in figure 2), the L would probably be too small at load pick-up and the counter-clockwise rotation might then even be reversed to a clockwise rotation, which could induce a fall forward. In short, loss of balance when picking up a load was prevented by specific preparations that yielded a large backward CoG momentum and a considerable counter-clockwise angular momentum at load pick-up. It is important to remember that load knowledge was required to execute these preparations, for absence of load knowledge yielded inadequate preparations in experiment II.

4.2. *Control of balance and lifting technique*

The preparatory changes described above were not exactly the same for the leglift and the backlift (figure 2 and table 1). This is interesting, because a difference in preparatory actions implies that the balance-threatening effect of load pick-up was not the same in both techniques. Although the backlift and leglift often have been subjected to research to identify and study differences in, for instance, low-back loading (Toussaint *et al.* 1992), metabolic energy expenditure (de Looze *et al.* 1992b) or spinal shrinkage (Van Dieën *et al.* 1994), differences in control of balance have never been assessed.

A significant difference in preparation between techniques was found for the p_{hor}, suggesting a differential effect of load pick-up on the body's CoG position. Without preparation (down I), the CoG_{rel} was positioned closer to the front margin of the base of support in leglifting compared with backlifting. The forward CoG shift at load pick-up was, therefore, more threatening when leglifting. Furthermore, a technique difference in the direction and magnitude of p_{hor} at load pick-up was observed. Without preparation, the leglift p_{hor} was about zero at load pick-up, while the backlift p_{hor} was negative, that is, directed backward. Hence, in backlifting, the forward CoG shift at load pick-up would be reversed by the backward p_{hor}, even without preparatory actions, whereas in leglifting the CoG would shift forward without being braked or reversed. Thus, these results suggest that preserving balance while picking up a load with a backlift was easier than while picking up the same load using a leglift. This suggestion is supported by the observation that in 44% of the leglift trials a loss of balance was observed, whereas this occurred in 36% of the backlift trials.

4.3. *Absence of load knowledge and low-back loading*

Epidemiological studies have demonstrated that some of the low-back injuries in industry are associated with falls, slips or trips that occur while lifting a load (Manning and Shannon 1981, Troup *et al.* 1981). Experiment II demonstrated that absence of load knowledge could lead to balance loss when the load mass was overestimated and, thus, may explain a part of the low-back pain incidence. The question is whether the mechanical load on the lumbar spine was indeed increased in

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The lower right panel presents the lumbo-sacral (L5-S1) torque of an additional experiment. Mean time traces ($n = 8$) ± 1 standard error of the mean of three different lifting tasks (16·7 kg expected, 6·7 kg that was expected to be 16·7 kg, and 6·7 kg expected) are shown. Time 0 indicates box lift-off, the moment at which the vertical force applied on the box exceeded the weight of the box. Note that the performance time of these tasks was considerably longer than the time of the tasks in the lower left panel, which explains the higher peak torques in that graph.

that case and, if so, whether the increase occurred in the preparatory phase or during the execution of postural reactions to regain balance.

The results of experiment II and the additional experiment demonstrated that the mechanical load on the lumbar spine was indeed increased when lifting an object without correct load knowledge, that is when the weight of the box was overestimated by 10 kg. Since subjects prepared themselves according to the expected load mass, no difference in low-back loading was observed between lifting a load of 16 kg and lifting a load of 6 kg that was expected to be 16 kg, until 150 ms after box lift-off (figure 4). Even the peak low-back loading was similar in both cases, although the actual mass difference was 10 kg. The peak low-back loading was, however, significantly lower when subjects lifted the 6 kg box with the correct load knowledge. Thus, the *expected* load mass largely determined the peak low-back loading, rather than the *actual* mass. This finding has important implications for existing guidelines for safe low-back loading limits. The NIOSH equation, for example, provides a method for computing weight limits for manual lifting based on the actual load mass and several factors that determine the functional load on the low back (Waters *et al.* 1993). The equation does not account for the expected load mass, which seems of more importance than the actual mass.

The postural reactions to prevent falling did not seem to affect low-back loading. Postural reactions presumably started 100 to 150 ms after box lift-off, as may be deduced from the sharp switch in the negative p_{hor} of the 6 kg trials (figure 4). Around that time, the low-back loading reached its peak and $T_{\mathrm{L5\text{-}S1}}$ of the overestimated 6 kg trials started to decrease with respect to $T_{\mathrm{L5\text{-}S1}}$ of the 16 kg trials.

4.4. *Absence of load knowledge and control of balance*

In 92% of all lifting trials in which subjects were induced to overestimate the box's weight, they lost balance, that is, they had to make serious efforts to prevent falling. Figure 4 elucidates what happened. Overestimating the load mass caused an overshoot in the linear and angular momenta; in the 6 kg trials, the backward and upward CoG momentum reached larger values than in the 16 kg trials. Thus, the subjects moved much faster backward and upward after box lift-off than intended, leading to imbalance. The existence of an overshoot in linear and angular momenta implies that the preparations in linear and angular momenta were not correct in the 6 kg trials. They were programmed to counteract the balance-disturbing effect of picking up a 16 kg load and, thus, were too large to match the effect of picking up a 6 kg load. Further details about adequately and erroneously programmed preparatory motor commands can be found in Toussaint *et al.* (submitted a). Thus, experiment II clearly demonstrated that the preparatory actions, aimed at minimizing the balance-threatening effect of load pick-up, were programmed according to the *expected* load mass, not according to the (unknown) *actual* load mass. It proves that load knowledge is essential for adequate programming of the preparations.

5. Conclusions and practical implications

In industrial whole-body lifting tasks, workers presumably prepare themselves also before they pick up a load. These preparations are directed at minimizing the risk of losing balance that is inherent in picking up a load in front of the body. They are based upon the expected load mass and are specific for the applied lifting technique. The preparations also determine the peak mechanical load on the lumbar spine. In cases where similar objects are continuously handled (e.g. at an assembly line), the preparations will be programmed on the basis of the weight of the previous object. Such a preparation will not be correct, however, when a similarly looking object of different weight is suddenly presented (the expectation pattern is disrupted). When the lifter overestimates the object's weight, an overshoot in the linear and angular momenta of the body will occur, leading to a disturbed balance, to twisting or jerking actions to regain balance and possibly to a fall. The low-back loading will resemble the low-back loading during lifting of the expected (overestimated) load mass, not of lifting the actual mass. In cases where the task comprises handling of objects varying in size and load mass, information about the weight of the previous object is not useful. The weight of each object will have to be estimated on the basis of its size, a common density and comparison with other objects (Gordon *et al.* 1991).

If workers are required to use programmed preparations, for instance when they have to lift at a predetermined, high pace, it is important to provide them with adequate information about the actual load mass. This implies (1) that the actual load mass has to be clearly and unequivocally displayed on the object in case objects of varying size, weight and unpredictable density are handled; (2) that workers should be trained in performing preparations that are adequate for the depicted load mass, because experience is required to perform adequate preparations when only visual information is present, and (3) that a pattern of expected load masses (for instance in an assembly line) should not be suddenly disrupted. With respect to guidelines for safe low-back loading limits, the expected load mass should be accounted for in situations without load knowledge, because the expected load mass seems to determine the low-back loading, rather than the actual mass.

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